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Bulletin 52

DEPARTMENT OF THE INTERIOR  
BUREAU OF MINES

JOSEPH A. HOLMES, DIRECTOR

IGNITION OF MINE GASES

BY THE FILAMENTS OF

INCANDESCENT LAMPS

BY

H. H. CLARK

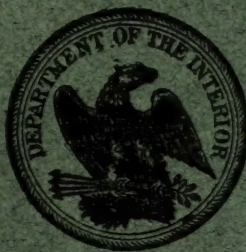
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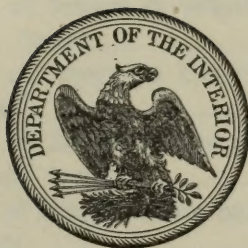
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IGNITION OF MINERAL LAMPS  
IN THE MINE  
INCANDESCENT LAMPS

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# IGNITION OF MINE GASES BY THE FILAMENTS OF INCANDESCENT LAMPS.

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By H. H. CLARK and L. C. ILSLEY.

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## INTRODUCTION.

As part of its investigations of the causes of mine accidents and of the safest and most efficient methods of handling electricity underground, the Bureau of Mines undertook a study of the ignition of mine gases by the filaments of electric incandescent lamps. This bulletin describes the investigation in detail and gives a complete record of the results obtained.

## PURPOSE OF THE INVESTIGATION.

The investigation was undertaken for the purpose of determining the degree of danger that attends the use of certain specific sizes of incandescent lamps in atmospheres containing inflammable gas. Previous investigators<sup>a</sup> have, to a greater or less extent, been concerned with certain theoretical features of the problem, such as the effect of the temperature and the dimensions of the lamp filaments and the question whether a lamp may ignite gas by the heat of its glowing filament or by the spark that is drawn when the filament is broken. Although these features were considered in the present investigation and are briefly discussed in this bulletin, the principal object of the tests was to determine what sizes of incandescent lamps suitable for mine use would ignite explosive mixtures of mine gas and air, and what were the circumstances most effective in causing such ignition.

## GENERAL STATEMENT OF RESULTS.

The results of the investigation may be generally summarized as follows:

The naked carbon filaments of standard lamps, burning at rated voltage, will invariably ignite explosive gaseous mixtures.

---

<sup>a</sup> Couriot, H., professor of mining methods, and Meunier, J., professor of chemistry, Central School of Arts and Manufactures, Paris, France; Heise, F., bergassessor, Gelsenkirchen, Westphalia, Germany; Thiem, Dr., engineer, Siemens-Halske Co., Berlin, Germany; Lemaire, Emanuel, professor, University of Louvain, and engineer, Frameries experiment station, Frameries, Belgium; Hauser, M., professor, Madrid School of Mines, Madrid, Spain; Stasart, A., professor, Hainault Mining and Polytechnic School, Hainault, France.



If gas can reach the filaments of standard lamps without breaking the filaments or producing partial combustion within the bulbs, the explosive gaseous mixture is sure to be ignited.

Several sizes of both standard and miniature lamps, when smashed while burning at rated voltage, will ignite gas.

Standard lamps that do not usually ignite explosive gaseous mixtures may do so if the broken pieces of the filament cause a short circuit when the lamps are smashed.

#### DEFINITIONS OF TERMS.

For convenience in reporting the results of the investigation, certain terms have been used in a somewhat specialized sense. The terms so used are defined below.

##### STANDARD—MINIATURE.

The lamps tested are referred to in this bulletin as either standard or miniature. Lamps classified as standard are incandescent lamps such as are used for the purposes of general illumination. These lamps were of various voltages, from 50 to 225, and of various candlepowers, from 8 to 50. Lamps classified as miniature are such lamps as are used for portable service. The voltages of these lamps were 1.5 to 6, and the candlepowers 0.2 to 2.0.

##### CLASS.

The term class is used to include all lamps of approximately equal voltage and candlepower, regardless of the brand of manufacture. Thus an 8-candlepower, 50-volt lamp and a 30-watt, 55-volt lamp are regarded as belonging to the same general class.

##### IGNITION—EXPLOSION.

The term ignition is used to denote the act of the filaments in causing the explosive mixtures to take fire. The term explosion is used to refer to the result of an ignition.

##### SERIES—TEST.

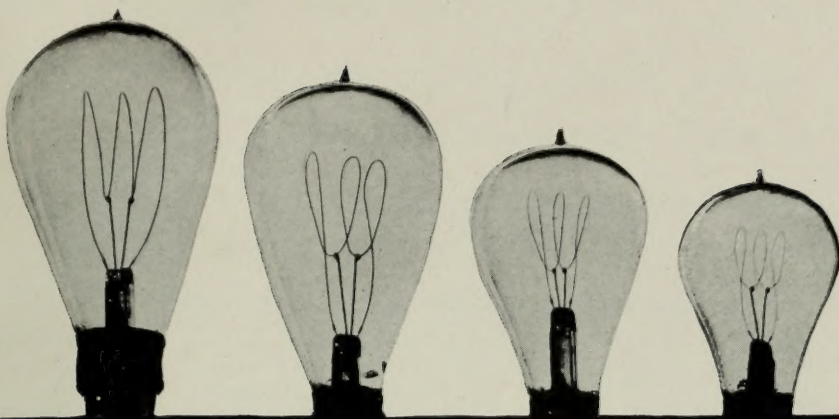
The term series is used to refer to one of the seven principal subdivisions of the investigation in each of which a large number of similar tests was made. The term test refers to a single trial to ignite an explosive mixture with any particular lamp.

##### LAMP—BULB.

The term lamp is used to refer to the combination of bulb, filament, and base. The term bulb is used to refer to the glass envelope of the filament.

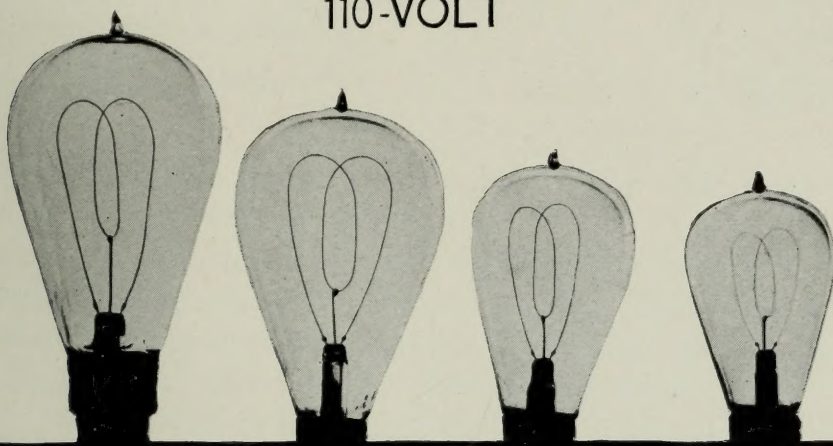


## 220-VOLT



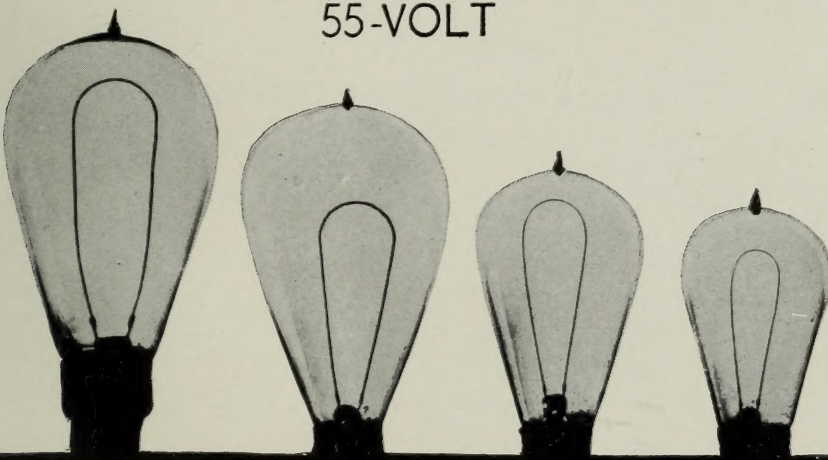
190 W., 50 C.P. 120 W., 32 C.P. 60 W., 16 C.P. 30 W., 8 C.P.

## 110-VOLT



155 W., 50 C.P. 120 W., 32 C.P. 60 W., 16 C.P. 30 W., 8 C.P.

## 55-VOLT



175 W., 50 C.P. 120 W., 32 C.P. 60 W., 16 C.P. 30 W., 8 C.P.

CLASSES OF STANDARD CARBON-FILAMENT LAMPS INVESTIGATED.







GAS.

The term gas, as used hereafter in this bulletin, refers to the natural gas used in the tests, or to a mixture of this gas and air.

DETAILS OF THE INVESTIGATION.

NUMBER AND KINDS OF LAMPS TESTED.

Lamps used in the investigation were supplied without charge to the bureau by certain companies, as follows:

*Lamps gratuitously supplied by manufacturers.*

| Company.                                | Number of lamps submitted. | Size.         | Character of filament. |
|-----------------------------------------|----------------------------|---------------|------------------------|
| General Electric Co.....                | 288                        | Standard....  | Carbon.                |
| Do.....                                 | 86                         | Miniature.... | Do.                    |
| Do.....                                 | 120                        | .....do.....  | Tungsten.              |
| National Electric Lamp Association..... | 288                        | Standard....  | Carbon.                |
| Do.....                                 | 48                         | Miniature.... | Tungsten.              |
| Westinghouse Lamp Co.....               | 192                        | Standard....  | Carbon.                |
| Federal Miniature Lamp Co.....          | 52                         | Miniature...  | Tungsten.              |

In addition, the bureau purchased in the open market standard lamps of five different brands.

One thousand one hundred and eighty-eight carbon-filament and 31 tungsten-filament standard lamps, also 42 carbon-filament and 192 tungsten-filament miniature lamps, were used in this investigation, including 125 kinds of lamps differing in candlepower, voltage, or brand. The tables following show the number of each size and the rating of the lamps used. Plate I shows the relative size of the standard lamps used and Plate II, A, shows the relative size of the miniature lamps.

TABLE 1.—*Number and rating of standard lamps tested.*

| Number used. | Approximate candlepower. | Range of rated wattage. | Rated voltage. | Character of filament. |
|--------------|--------------------------|-------------------------|----------------|------------------------|
| 30.....      | 8                        | 28                      | 50             | Carbon.                |
| 101.....     | 8                        | 25-30                   | 55             | Do.                    |
| 10.....      | 16                       | 55                      | 50             | Do.                    |
| 92.....      | 16                       | 50-60                   | 55             | Do.                    |
| 64.....      | 32                       | 100-120                 | 55             | Do.                    |
| 25.....      | 50                       | 155-175                 | 55             | Do.                    |
| 125.....     | 8                        | 25-30                   | 110            | Do.                    |
| 160.....     | 16                       | 50-60                   | 110            | Do.                    |
| 92.....      | 32                       | 100-120                 | 110            | Do.                    |
| 8.....       | 32                       | 110                     | 127            | Do.                    |
| 30.....      | 50                       | 155-175                 | 110            | Do.                    |
| 115.....     | 8                        | 28-35                   | 220            | Do.                    |
| 131.....     | 16                       | 55-60                   | 220            | Do.                    |
| 149.....     | 32                       | 110-120                 | 220            | Do.                    |
| 56.....      | 50                       | 175-190                 | 220-225        | Do.                    |
| 11.....      | 20                       | 25                      | 110            | Tungsten.              |
| 20.....      | 20                       | 25                      | 220            | Do.                    |

Total number of standard lamps used, 1,219.



TABLE 2.—*Number and rating of miniature lamps tested.*

| Number used. | Manufacturer's rating. |          |               | Character of filament. |
|--------------|------------------------|----------|---------------|------------------------|
|              | Volts.                 | Amperes. | Candle-power. |                        |
| 12.....      | 1.5                    | 0.40     | 0.50          | Tungsten.              |
| 12.....      | 2.0                    | .23      | .....         | Do.                    |
| 9.....       | 2.0                    | .40      | .....         | Do.                    |
| 9.....       | 2.0                    | .....    | 1.00          | Do.                    |
| 12.....      | 2.0                    | .43      | .....         | Do.                    |
| 5.....       | 2.0                    | .53      | .....         | Do.                    |
| 5.....       | 2.0                    | .73      | .....         | Do.                    |
| 23.....      | 2.5                    | .30      | 1.00          | Do.                    |
| 16.....      | 2.5                    | .....    | 1.00          | Do.                    |
| 44.....      | 3.5                    | .30      | 1.50          | Do.                    |
| 10.....      | 4.0                    | .....    | 2.00          | Do.                    |
| 5.....       | 4.0                    | .53      | .....         | Do.                    |
| 10.....      | 4.5                    | .....    | 2.00          | Do.                    |
| 21.....      | 5.5                    | .30      | 2.00          | Do.                    |
| 5.....       | 6.0                    | .30      | .....         | Do.                    |
| 7.....       | 2.5                    | .....    | .....         | Carbon.                |
| 22.....      | 3.5                    | .....    | .....         | Do.                    |
| 13.....      | 5.5                    | .....    | .....         | Do                     |

Total number of miniature lamps used, 234.

TEST CONDITIONS AND EQUIPMENT.

CHARACTER OF GAS USED.

Natural gas from the Pittsburgh city mains was used in all tests. The composition of this gas is approximately 82 per cent methane, 16.4 per cent ethane, 1.5 per cent nitrogen, and a trace of carbon dioxide.<sup>a</sup>

The lamps under test were surrounded by gas that was at rest. No tests were made in a current of gas, because gas in motion is not so easily ignited as gas at rest, and it was the intention to make the test conditions as severe as possible.

The lamps were tested in a gas-tight receptacle (Pl. III) filled with a mixture of gas and air. The usual proportion was 8.6 per cent gas to 91.4 per cent air, which is the most explosive combination of the natural gas used and air. The percentage of gas, however, was increased or decreased for some of the tests.

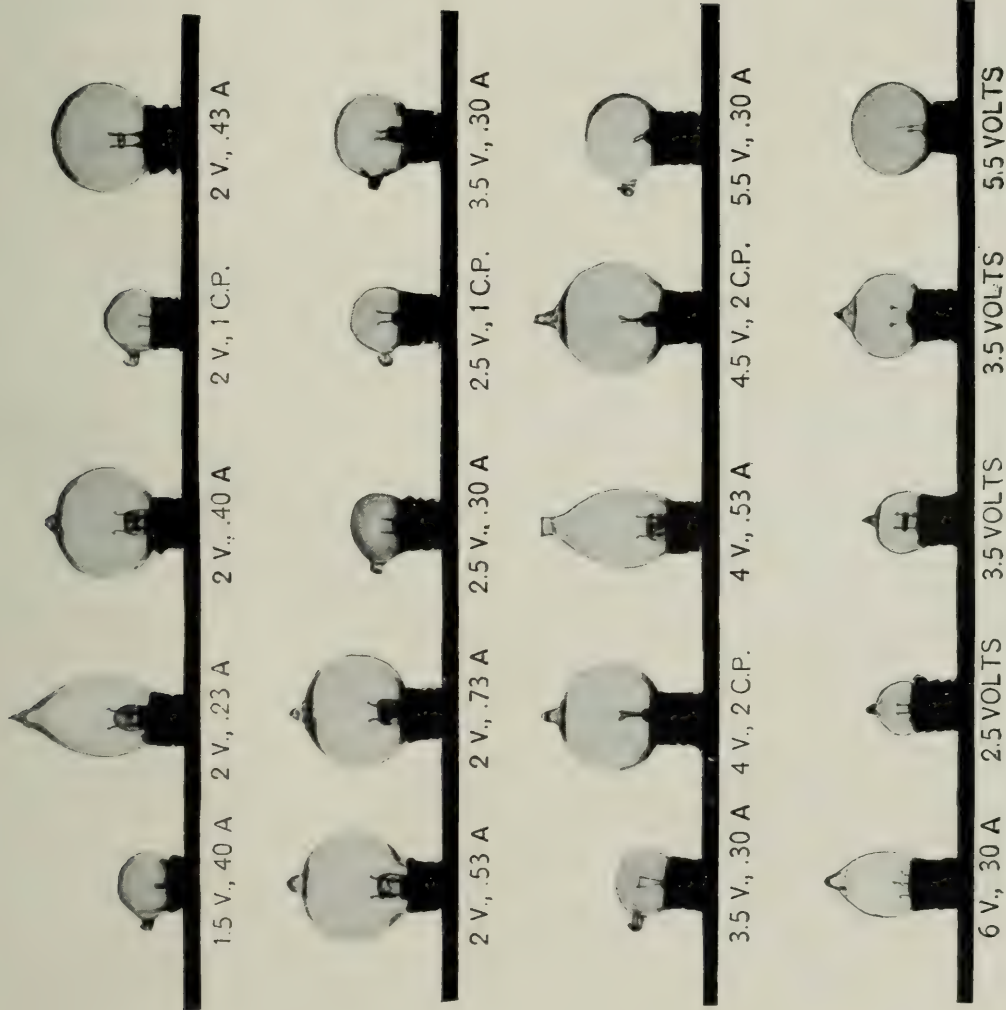
METHODS OF ADMITTING GAS TO BULBS.

The way in which an explosive mixture enters the bulb of an incandescent lamp has an important bearing upon whether the mixture will be ignited by the lamp filament. Accidental entrance to the bulbs of lamps in practical use occurs when the bulbs are completely smashed or the tips are broken from the bulbs.

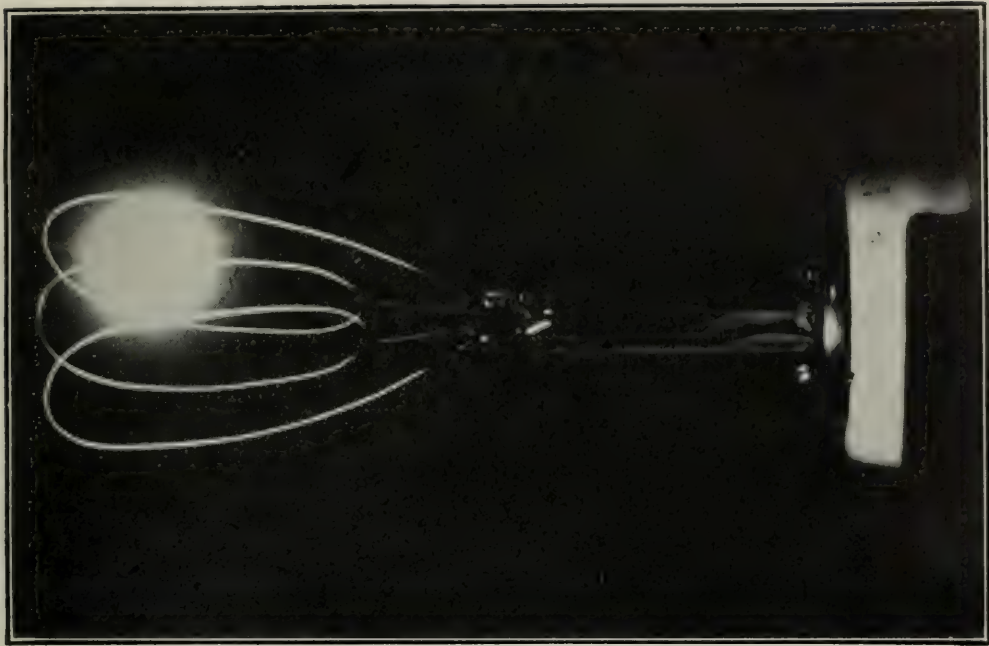
The smash tests, embraced in series 1, 1-A, 1-B, 1-C, and 1-D, and the tests of series 2, comprising the tip-breaking tests, were made to imitate the two means of entrance indicated. The tests of series 3,

<sup>a</sup> Burrell, G. A., Bull. 15, Bureau of Mines, 1911, p. 66.





A. CLASSES OF MINIATURE LAMPS INVESTIGATED. BEGINNING AT UPPER LEFT-HAND CORNER, THE LAMPS FOLLOW THE ORDER GIVEN IN TABLES 2 AND 6.



B. NAKED FILAMENT OF STANDARD LAMP, SHOWING "HOT SPOT."







embracing the puncture tests, were made to determine what would happen if an explosive mixture should enter a bulb in such a manner as not to impinge directly upon the filament. The tests of series 4, comprising the naked-filament tests, were made to determine the action of filaments burning to extinction in explosive mixtures. The tests of series 1 included five different sets of conditions. The tests of the other series were made under only one set of conditions.

The table following gives the conditions under which each test was made:

TABLE 3.—Conditions in each series of tests.

| Series No. | Kind of lamps used.       | Method of breaking bulbs. | Voltage impressed. | Gas percentage. | Character of current. | Connection of lamps. |
|------------|---------------------------|---------------------------|--------------------|-----------------|-----------------------|----------------------|
| 1.....     | Standard a n d miniature. | Smashing.....             | Rated.....         | 8.6             | Direct.....           | Multiple.            |
| 1-A.....   | Standard.....             | do.....                   | do.....            | 8.6             | Alternating.....      | Do.                  |
| 1-B.....   | do.....                   | do.....                   | do.....            | 8.6             | Direct.....           | Series.              |
| 1-C.....   | Standard a n d miniature. | do.....                   | do.....            | Various.        | do.....               | Multiple.            |
| 1-D.....   | do.....                   | do.....                   | More than rated.   | 8.6             | do.....               | Do.                  |
| 2.....     | Standard.....             | Breaking tip.....         | Rated.....         | 8.6             | do.....               | Do.                  |
| 3.....     | do.....                   | Puncture.....             | do.....            | 8.6             | do.....               | Do.                  |
| 4.....     | Standard a n d miniature. | (a).....                  | do b.....          | 8.6             | do.....               | Do.                  |

a In each of the series 4 tests the glass bulb was removed and rated voltage was impressed upon the naked filament after it had been surrounded with gas.  
b It was necessary to use more than rated voltage in order to obtain ignitions from the miniature lamps in the tests of this series.

TESTING EQUIPMENT.

The equipment used in making the tests consisted of the following apparatus: A gas-tight box or gallery (Pls. III and IV) for containing the gaseous mixture in which the lamps were tested; a gas meter for measuring the amount of gas used in the testing mixture; suitable mountings for holding the lamps in proper position for breaking (Pl. V).

Direct current for testing the standard lamps was obtained from a motor-generator set. Alternating current at 60 cycles was taken from a transformer, and direct current for the miniature lamps was supplied by storage or primary batteries.

TESTING GALLERY.

The testing gallery (Pls. III and IV) was a rectangular boiler-iron box, 18 by 18 by 24 inches, provided with a glass door, two observation windows, and a circular opening 13 inches in diameter at the top of the box to relieve the pressure developed by an explosion. This opening was covered by a sheet of paper coated with paraffin and held in place by a heavy iron ring. The electrical connections were brought into the gallery through gas-tight bushings. A sliding rod for breaking the lamps penetrated the side of the gallery through a gas-tight steel bushing.

The gallery was equipped with a small circulating fan directly connected to a  $\frac{1}{20}$ -horsepower electric motor (Pl. III). The fan intake and the fan discharge were connected to the same end of the gallery. The fan could be entirely isolated from the gallery by means of quick-closing valves. The gas-intake connection was made directly to the gallery near the fan discharge, and at the same point a supply of compressed air was also connected for clearing the gallery of dead gases after each test.

#### GAS METER.

The gas meter was designed to measure very small quantities of gas and could be read with satisfactory accuracy to 0.001 of a cubic foot. The quantity of gas that was necessary to admit to the gallery in order to obtain a desired percentage of gas in the testing mixture was determined periodically by chemical analysis.<sup>a</sup>

#### LAMP HOLDERS.

Two different holders were used for mounting the lamps during test. One holder (Pl. V, *A*) was used only in the smash tests for holding the bulbs rigidly at a point where they could be struck squarely by the sliding rod. The other holder (Pl. V, *B*) was used in both the tip-breaking tests and the puncture tests. In the tip-breaking tests the latter holder supported the bulb firmly in position while a spring-actuated arm, which was part of the holder, swept across the tip of the bulb and broke it off clean. In the puncture tests the same holder (Pl. V, *C*) kept the bulb suspended in proper relation to two pointed rods fitted into small indentations made in the bulb by a blowpipe flame. One of the rods was movable. Upon closing a switch, the spring-actuated arm mentioned above swept around and struck the movable rod a blow sufficient to punch a small hole in the bulb. The arm was operated by a spring held in tension by a hooked catch and released by an electromagnet which could be operated from outside the gallery.

#### CHARACTER OF THE TESTS IN THE DIFFERENT SERIES.

The several methods of testing the lamps are detailed below.

#### SMASH TESTS.

Tests of the effects of breaking the bulbs were classified under series 1, 1-A, 1-B, 1-C, and 1-D as described below:

#### SERIES 1, LAMPS ON DIRECT CURRENT.

For the smash tests in which the lamps were on direct current, each lamp was mounted in the holder (Pl. V, *A*) and placed in the

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<sup>a</sup> These analyses were made by G. A. Burrell, chemist, of the Bureau of Mines.





TESTING GALLERY, SHOWING CIRCULATING FAN.





gallery. The current consumption of the lamp at rated voltage was measured and the gallery was closed and filled with a mixture of air and 8.6 per cent gas. The lamp was lighted and the bulb was smashed by striking the breaking rod with a hammer (Pl. IV). After all observations had been recorded, the gallery was aired out for the next test. Both miniature and standard lamps were tested in this manner.

SERIES 1-A, LAMPS ON ALTERNATING CURRENT.

The smash tests of series 1-A were identical with those of series 1, except that alternating current was used instead of direct current. The purpose of the series was to determine whether the character of the current had an influence upon the tendency of the lamps to ignite gaseous mixtures. Only standard lamps were tested in this manner.

SERIES 1-B, LAMPS CONNECTED IN SERIES.

The smash tests of series 1-B were identical with those of series 1, except that the lamp under test was in series with one or more similar lamps, the voltage impressed across the series of lamps being of such a value as to give the rated voltage across the terminals of the test lamp. The object of this series of tests was to determine whether the series connection of lamps increases the risk attending the use of such lamps in mines. Only standard lamps were tested in this manner.

SERIES 1-C, GAS PERCENTAGES VARIED.

The tests of series 1-C were also identical with those of series 1, except that the percentages of gas used in the explosive mixture were increased or decreased. The purpose of the tests was to determine whether the lamps would ignite all mixtures containing percentages of gas that were between the explosive limits of the gas. Both miniature and standard lamps were tested in this manner.

SERIES 1-D, VOLTAGE MORE THAN RATED.

In the smash tests of series 1-D a lamp was mounted in the holder and placed in the gallery. The consumption of current by the lamp at a predetermined voltage was measured and the gallery was then closed and filled with gas, the lamp was lighted, and the bulb was smashed by striking the breaking rod with a hammer. The gallery was thoroughly aired after the observations had been recorded. The object of this series of tests was to determine the amount of excess energy that would be required to cause ignition of gas by lamps that did not ignite gas at rated voltage. The results thus obtained provide a means for comparing the relative safety of the different classes of standard lamps when the bulbs are smashed by a direct blow.

## GENERAL BEHAVIOR OF LAMPS IN SMASH TESTS.

The general behavior of the lamps in the tests of series 1, 1-A, 1-B, 1-C, and 1-D was the same. With three exceptions, the filaments of standard lamps were broken when the bulbs were smashed, but the miniature-lamp filaments usually remained intact. Ignitions, when they occurred in the tests of standard lamps, seemed to take place almost simultaneously with the blow of the breaking hammer, but in some of the miniature-lamp tests the ignition of gas was delayed until several seconds had elapsed after the bulb had been broken. In most tests the bulb was practically destroyed by the blow. In a few tests the breaking rod merely made a hole in the side of the bulb.

Ignitions from standard lamps, especially from those having a high current consumption, were more violent than ignitions resulting from the miniature-lamp tests. The ignitions obtained when the gas percentages were more or less than 8.6 per cent were less violent than those obtained with 8.6 per cent gas. The diminution of violence was, however, more marked with the lower percentages of gas.

When carbon filaments burned in air or gas the cooling of the filaments caused a decrease in the current consumption. The converse was true of the tungsten filaments. The carbon filaments of the miniature lamps were cooled to such an extent that they burned at a dull red glow, the current consumption being greatly reduced, so that sufficient heat to produce ignition was not developed at the point where the filaments ruptured. The tungsten filaments of the standard lamps were probably broken by the jar from the hammer blow before the gas came in contact with them, but they either retained sufficient heat to ignite the gas when they came in contact with it (as in the case of the 25-watt, 110-volt lamps), or (as in the case of the 25-watt, 220-volt lamps) the pieces of the broken filament short-circuited and thus produced ignition.

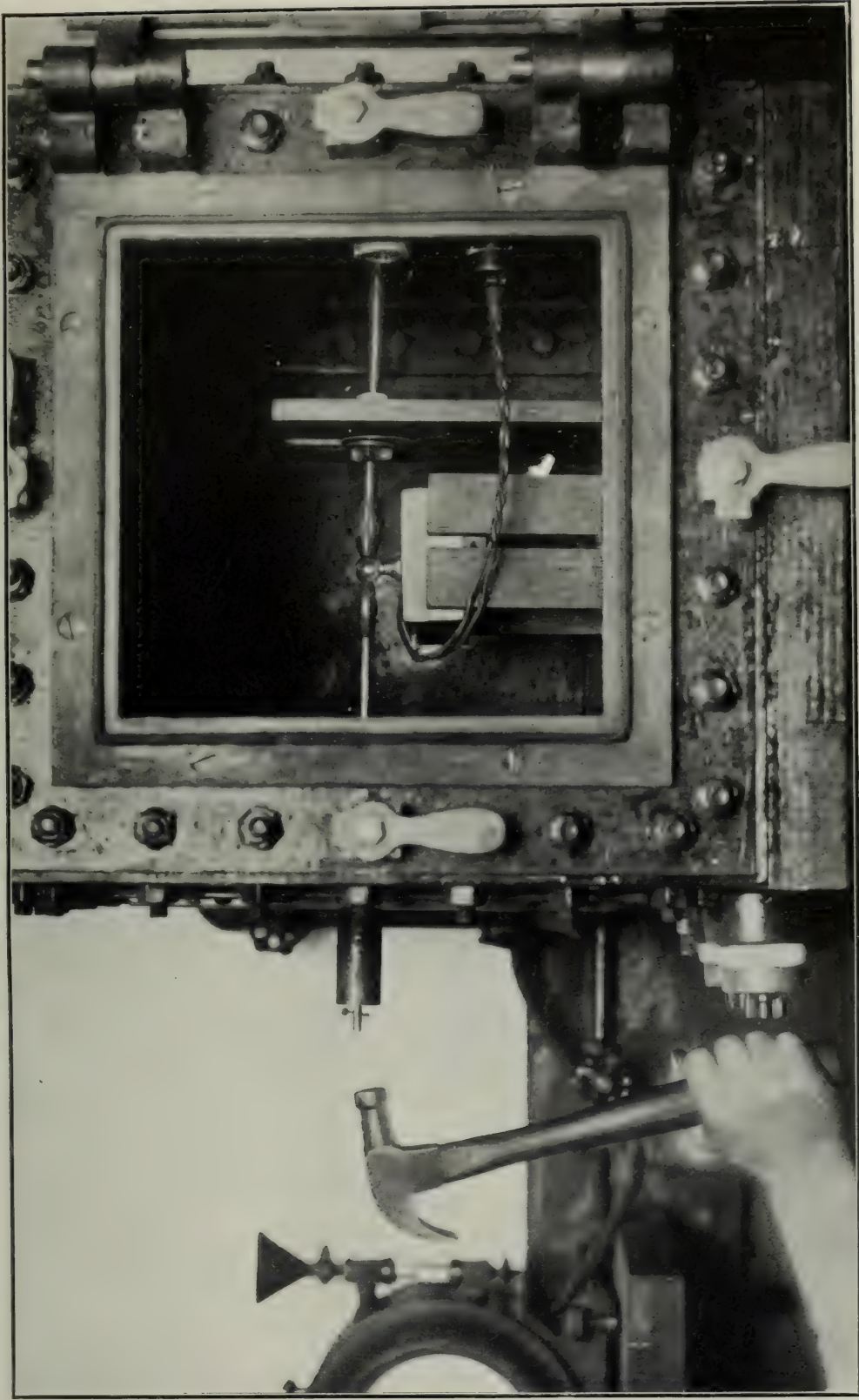
## SERIES 2, TIP-BREAKING TESTS.

For the series 2 tests a lamp was mounted in the holder (Pl. V, *B*) and placed in the gallery. The current consumption at rated voltage was measured and the gallery was closed and filled with gas. The breaking arm was then released and allowed to sweep across the top of the bulb in such a manner that a part of the tip was broken off. The observations were recorded and the gallery aired. The purpose of these tests was to determine the danger incident to breaking lamps in this manner. Only standard lamps were subjected to this series of tests.

## GENERAL BEHAVIOR OF LAMPS IN THE TIP-BREAKING TESTS.

Lamps tested under the conditions of the series 2 tests were affected in three different ways. The lamps tested may be classified, according to the action of the entering gas upon their filaments, as





TESTING GALLERY, SHOWING MINIATURE LAMP IN POSITION FOR BREAKING.





lamps with broken filaments (Pl. VI, *A*), lamps with cooled filaments, and lamps with uncooled filaments. Lamps of the first class never ignited the gas, and require no further comment. Of the lamps with cooled filaments those with the larger filaments usually recovered their temperature without delay and ignited both the gas within the bulb and that surrounding it. Those with the smaller filaments (Pl. VI, *B*) recovered their temperature more slowly, requiring from one to five minutes to ignite the gas. The ignitions from these smaller filaments were generally produced by "hot spots." Plate II, *B*, shows a typical hot spot at the point of rupture. These hot spots occurred at points on the filament where oxidation was more rapid and where the dissipation of energy by the filament was concentrated, as shown by a marked increase in the brilliancy of the filament and subsequent burning at such points. Ignitions caused by hot spots usually occurred just before, or coincident with, the rupture of the filament.

Filaments that were not cooled by the entering gas generally ignited it before the bulbs had filled with gas, thus effecting an ignition not violent enough to destroy the bulb. Part of the products of the ignition remained within the bulb and, upon cooling, became mixed with a fresh supply of incoming gas, and a second ignition weaker than the first was produced. This process continued until the bulb became filled with inert gases. These gases surrounded the burning filament and delayed its oxidation, so that it glowed for a longer period than if surrounded by air. Several consecutive ignitions occurred within the bulb in most tests of this class. Such ignitions were manifested by alternate increase and decrease in the deflection of the ammeter and by the darkening and brightening of the filament. The first two or three ignitions usually produced a hissing noise due to the expulsion of the gases through the small opening in the bulb.

The size of the hole made by the breaking arm was an important factor in producing ignitions. With the larger filaments large holes were more likely to produce ignition than were small ones. Whenever the breaking arm made a sufficiently large hole in the bulb, the entering gas would cool the filament long enough to allow the bulb to become filled with gas. When the inrush of gas had ceased, the filament would at once recover its normal temperature and ignite the gas within and surrounding the bulb. In many such tests the filament continued to glow for several seconds after ignition had taken place.

#### SERIES 3, PUNCTURE TESTS.

The lamps were prepared for the series 3 tests by indenting the necks of the bulbs at diametrically opposite points by means of a blowpipe flame. The indentations were then covered with pieces of

paper the size of a postage stamp. The purpose of the paper was to regulate the size of the hole made by the puncturing rod. The hole made in the paper was usually less than that made through the glass and therefore regulated to some extent the velocity of the entering gas.

The lamp, having been properly prepared, was placed in the holder (Pl. V, *C*) in such a manner that the pointed ends of the puncturing rods entered the indentations in the neck of the bulb. The holder was placed in the gallery and the current consumption of the lamp at rated voltage was measured. The gallery was then closed and filled with gas, the lamp was lighted, and the bulb was punctured. The puncture was caused by a blow from the breaking arm, which in this case was so adjusted as to strike a sliding rod, the pointed end of which was placed in one of the indentations in the lamp. The purpose of these tests was to study the action of the filaments upon gas that entered the bulb in such a way as not to injure the filament.

#### GENERAL BEHAVIOR OF LAMPS IN THE PUNCTURE TESTS.

The action of the filaments in these tests was similar to that observed in the series 2 tests, except that, owing to the manner in which the gas entered the bulb, fewer filaments were destroyed by the entering gas and consequently more explosions resulted.

#### SERIES 4, NAKED-FILAMENT TESTS.

The glass was carefully removed from around the filament, and the base, together with the naked filament, was mounted in the holder and placed in the gallery. The gallery was closed and filled with gas. Current<sup>a</sup> was then impressed on the naked filament. The object of the series 4 tests was to observe the action of unbroken filaments burning in a gaseous mixture. Both miniature and standard lamps were tested in this manner.

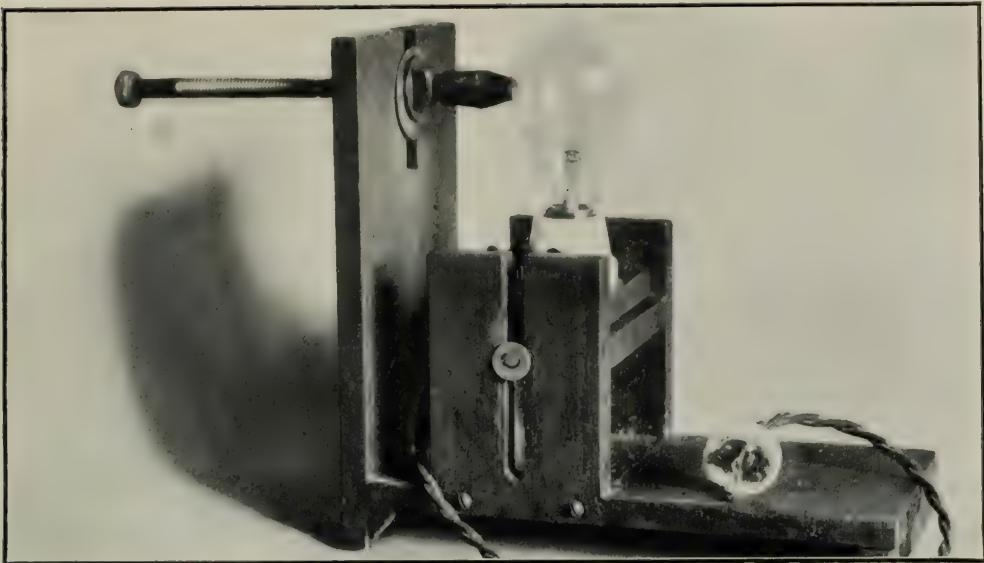
#### GENERAL BEHAVIOR OF LAMPS IN THE NAKED-FILAMENT TESTS.

In this series there were among the standard lamps no failures to ignite gas although ignitions were sometimes delayed. The larger filaments ignited the gas practically as soon as current was impressed upon them, smaller filaments ignited the gas after an appreciable interval, and the smallest filaments sometimes burned for several minutes before ignition occurred. In such tests ignition was caused by a hot spot in the filament. As the oxidation of the filament progressed the resistance of certain sections increased to such a

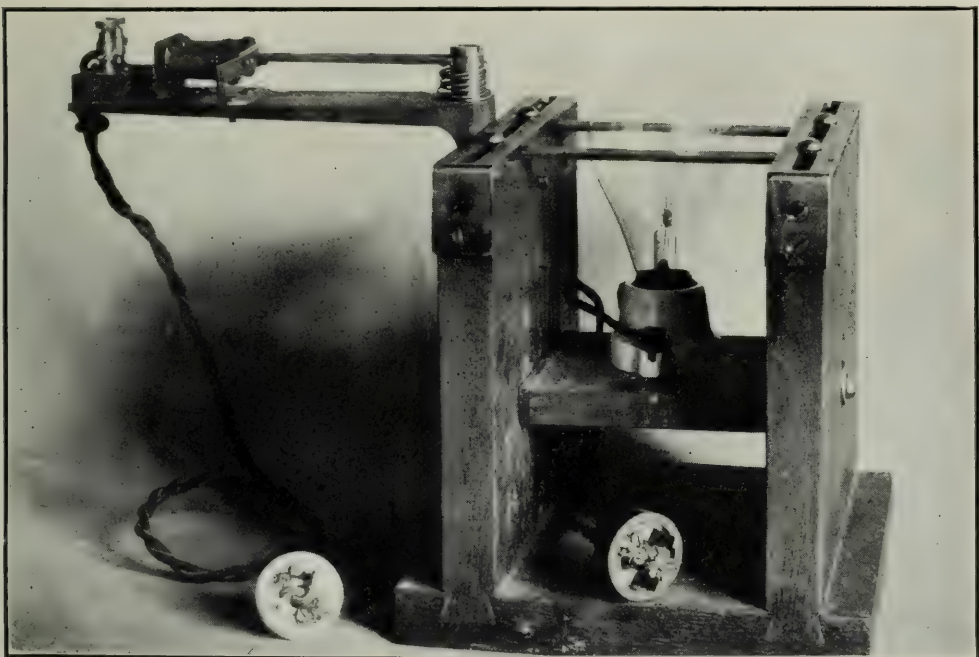
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<sup>a</sup> Rated voltage in the case of standard lamps and more than rated voltage in the case of miniature lamps.

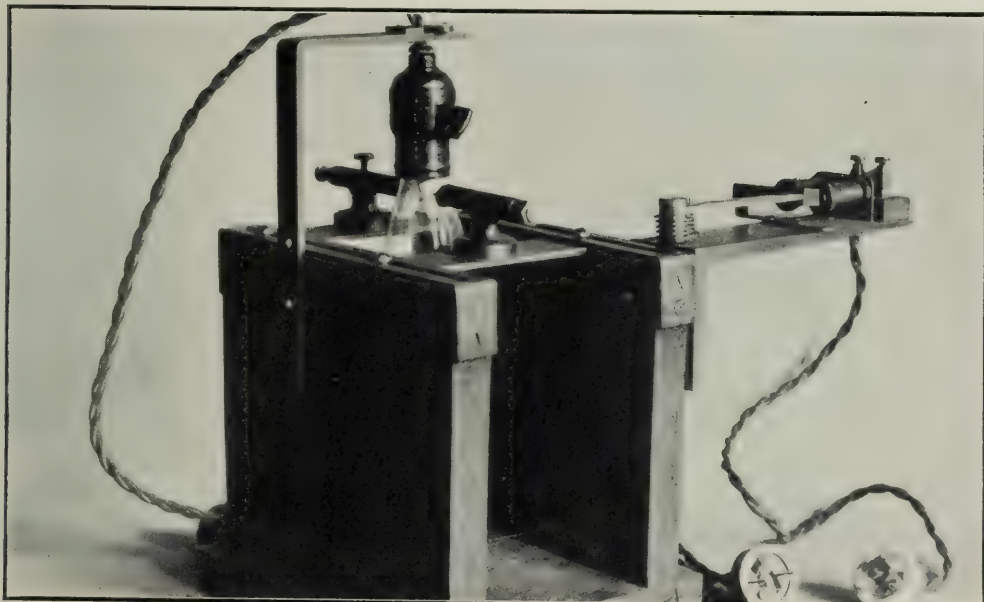




A. HOLDER USED IN SMASH TESTS.



B. HOLDER USED IN TIP-BREAKING TESTS



C. HOLDER USED IN PUNCTURE TESTS.





degree that almost all of the energy absorbed by the lamp was concentrated in those sections. The temperature of those sections rose to a degree which, judged by the eye, equalled or exceeded the normal temperature of the filament in a vacuum. In the majority of tests of standard lamps the filaments burned off after the gas had ignited.

#### EXCEPTIONAL TEST RESULTS.

The results of the investigation as a whole were satisfactorily consistent. Quite as satisfactory, however, were a few tests whose results were the exact opposite of what was to be expected. Some of the exceptional results are mentioned below and are of interest as showing a few of the possible variations in the behavior of the lamps.

Lamp 161, rated 190 watts at 220 volts, and lamps 146 and 171, rated 120 watts at 55 volts, were smashed under series 1 conditions. These were the only standard lamps whose filaments were not broken when the bulbs were smashed. Each lamp gave an immediate ignition when the bulb was broken, the filaments continuing to glow 5 to 20 seconds after the ignition.

Lamp 172, rated 60 watts at 110 volts, was smashed and ignited the gas under series 1 conditions. This was the only ignition resulting from 22 trials, and was probably caused by a short circuit of the filament. This theory is confirmed by the results of subsequent tests made with lamps 617, 646, 706, 800, 897, and 923 in which short circuits were known to have occurred.

Lamp 617, rated 60 watts at 110 volts, was smashed under series 1 conditions. The anchored loop of the filament swung downward and short-circuited the leading-in wires, thus causing ignition of the gas.

Lamp 906, rated 30 watts at 110 volts, was punctured under series 3 conditions. The gas within the bulb was ignited, destroying the bulb but not igniting the gas surrounding it. This was the only test in which the gas surrounding the bulb was not ignited when the explosion within the bulb was sufficiently violent to destroy it. When the bulb was punctured the entering gas cooled the filament to blackness, but it recovered its temperature almost immediately and, after burning with a dull red color for 35 seconds, began to glow more brilliantly. At the end of 47 seconds the gas within the bulb ignited with a sharp, snappy report, completely destroying the bulb, but failing to ignite the gas surrounding it.

Lamps 672 and 683, rated 120 watts at 220 volts, were tested under series 2 (tips broken) conditions. These tests, although similar to many others of the same series, were noteworthy because of the length of time required for the filaments to oxidize. The filaments of both



lamps glowed for more than five minutes before they burned off, and did not ignite the gas in the gallery. The test of lamp 683 was also interesting because 18 distinct ignitions were observed within the bulb. The removal of the tip left a hole  $\frac{1}{16}$  inch in diameter. The incoming gas, failing to cool the filament, was ignited before much gas had entered the bulb. The resulting explosion was, therefore, weak and did not injure the bulb. The inflow of gas was momentarily checked, but was almost immediately reestablished by the cooling of the products of combustion within the bulb. The filament, still glowing at nearly normal brilliancy, once more ignited the entering gas and the cycle of events was repeated 17 times in about five seconds with constantly decreasing strength.

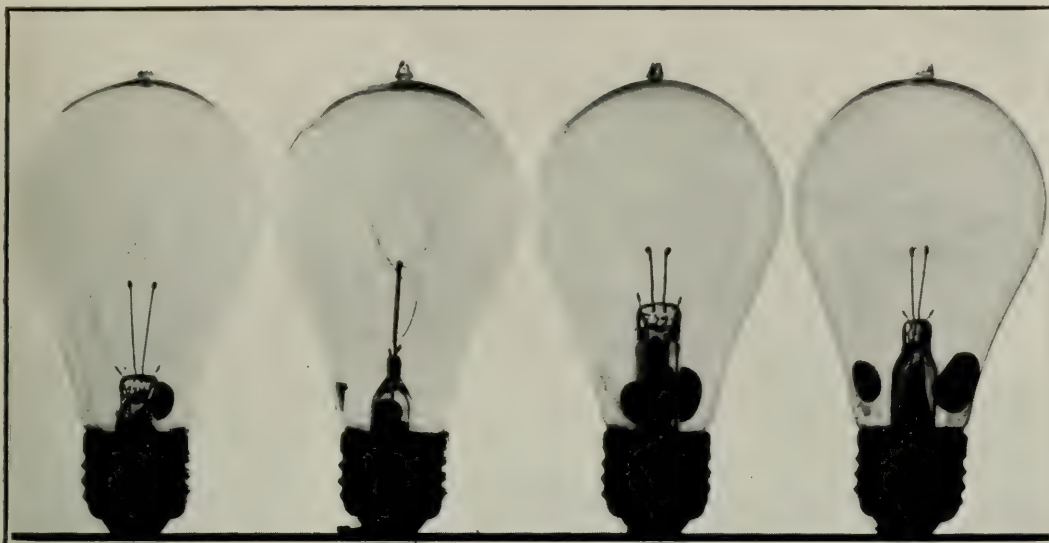
Lamp 898, rated 60 watts at 220 volts, when punctured gave a delayed ignition. Lamps of this class usually caused almost immediate ignition when the lamp filaments were not broken by the gas. In the test of this particular lamp the ignition occurred 53 seconds after the bulb had been punctured. The delay of the ignition was probably due to a large opening in the bulb which permitted the entering gas to cool the filament below the ignition temperature of the mixture. The filament did not recover its temperature at once, but burned at a dull red hue, not having sufficient temperature to ignite the gas until the heat became concentrated at a single point. The filament then ignited the gas within the bulb, the explosion destroying the bulb and igniting the surrounding gas.

Lamp 780, rated 120 watts at 55 volts, was tested under series 2 (tip broken) conditions, and caused an ignition of gas. This test was one of several in which the filaments continued to burn for several seconds after ignition had taken place. In this particular test ignition occurred almost as soon as the tip had been broken. The resulting explosion destroyed the bulb and ignited the gas surrounding it but did not injure the filament, which burned for 22 seconds before rupturing at one of three hot spots.

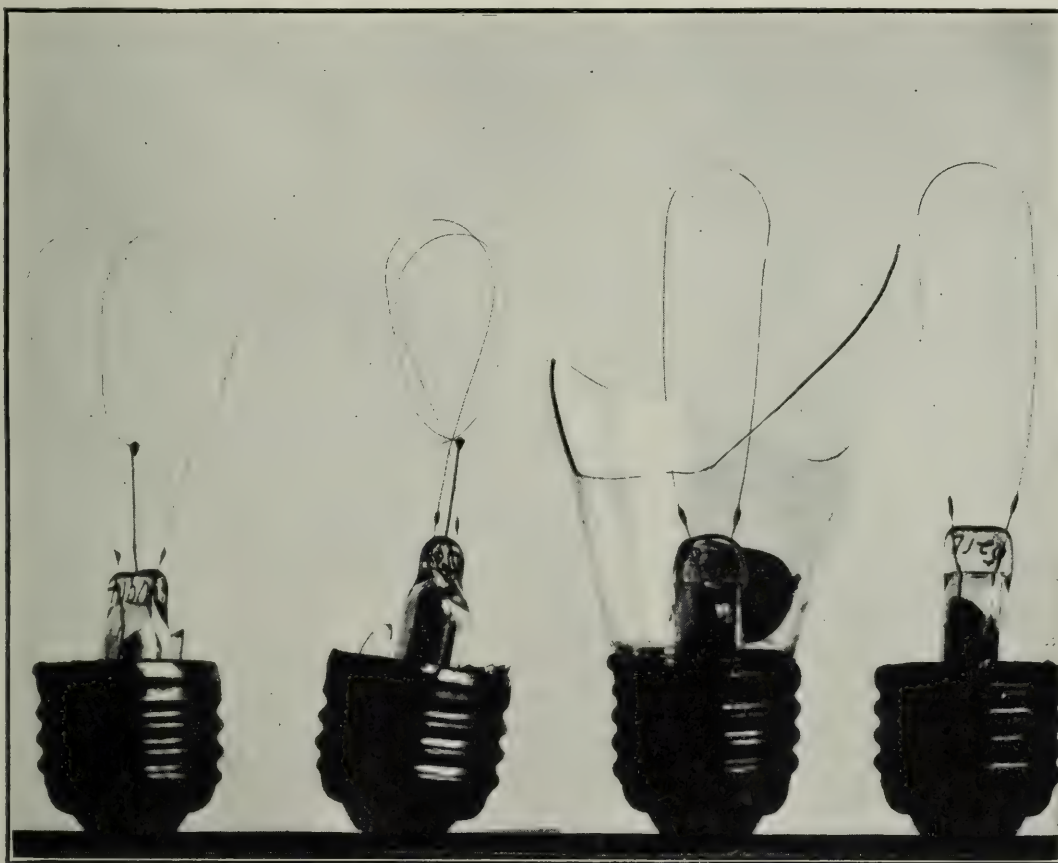
Lamp 686, rated 16 candlepower at 110 volts, was tested under series 2 conditions. The tip was so broken that a hole less than one sixty-fourth inch in diameter resulted. The gas entered so slowly that its effect upon the filament was imperceptible. There was no explosion within the bulb, an indication that the gas burned as it entered. The filament developed two hot spots and burned off at one five minutes from the time of breaking the tip.

Lamp 728, rated 30 watts at 55 volts, was tested under series 2 (tip broken) conditions. The filament was slightly cooled as the gas entered, but recovered its temperature and in about two seconds ignited the gas within the bulb, completely destroying it. The filament then burned in the surrounding gas approximately four seconds before igniting it. The filament was not injured by either igni-





A. LAMPS IN TIP-BREAKING TEST, SHOWING FILAMENTS DISTORTED AND BROKEN BY THE ENTERING GAS.



B. LAMPS IN TIP-BREAKING TEST, SHOWING FILAMENTS THAT BURNED OFF AFTER IGNITING THE GAS.





tion, but burned off at a hot spot nine seconds after the tip had been broken.

Lamp 840, rated 190 watts at 220 volts, was tested under series 2 conditions. The filament was broken off at one leading-in wire by the entering gas. Six flashes were observed within the bulb, which became filled with a smoky vapor. The vapor was later found to have been due to the vaporizing of the substance used to secure the filament to the leading-in wires. The loosened filament made and broke the circuit at this point, causing a slight deflection of the ammeter. The gas within the bulb was not ignited by these flashes.

Lamp 810, rated 120 watts at 110 volts, was tested under series 2 conditions and caused an ignition of both the gas within the bulb and the surrounding gas. This test was exceptional in that a distinct report was heard for each of the two ignitions. Usually when an ignition within the bulb destroyed the bulb the ignition of the surrounding gas followed so quickly that only one report was audible.

Lamp 923, rated 35 watts at 220 volts, ignited the gas when tested under series 3 conditions. When the bulb was punctured there occurred a severe short circuit which, although instantly relieved by the line fuses, registered four times normal current on the ammeter and burned off the leading-in wires close to the glass.

#### RESULTS OF STANDARD LAMP TESTS.

##### TABULATION.

A tabulation of the results of the tests of standard lamps follows.

TABLE 4.—*Number of tests made with standard lamps and percentage of ignitions obtained.*

| Rating of lamps. <sup>a</sup>  | Series 1, 1-A, and 1-B (smash tests, rated voltage—lamps on direct current; lamps on alternating current; lamps in series). |                        | Series 1-C (smash tests—gas percentages varied). |                        | Series 1-D (smash tests—voltage more than rated). <sup>b</sup> |                                                                    |                         | Series 2 (tip-breaking tests). |                                                |                         |                        | Series 3 (puncture tests).                     |                         |                        | Series 4 (naked-filament tests). |
|--------------------------------|-----------------------------------------------------------------------------------------------------------------------------|------------------------|--------------------------------------------------|------------------------|----------------------------------------------------------------|--------------------------------------------------------------------|-------------------------|--------------------------------|------------------------------------------------|-------------------------|------------------------|------------------------------------------------|-------------------------|------------------------|----------------------------------|
|                                | Number of lamps tested.                                                                                                     | Per cent of ignitions. | Number of lamps tested.                          | Per cent of ignitions. | Number of ignitions.                                           | Minimum per cent of normal wattage, causing ignition. <sup>c</sup> | Number of lamps tested. | Per cent of ignitions.         | Per cent of ignitions from unbroken filaments. | Number of lamps tested. | Per cent of ignitions. | Per cent of ignitions from unbroken filaments. | Number of lamps tested. | Per cent of ignitions. |                                  |
| 8 candlepower, 50 volts.....   | 4                                                                                                                           | 0                      | .....                                            | .....                  | 2                                                              | 133.3                                                              | 5                       | 0                              | 0                                              | .....                   | .....                  | .....                                          | .....                   | .....                  |                                  |
| 8 candlepower, 55 volts.....   | 5                                                                                                                           | 0                      | .....                                            | .....                  | .....                                                          | .....                                                              | 5                       | 40                             | 50                                             | 4                       | 100                    | 100                                            | 4                       | 100                    |                                  |
| 30 watts, 50 volts.....        | 4                                                                                                                           | 0                      | .....                                            | .....                  | 4                                                              | 146.8                                                              | 5                       | 40                             | 40                                             | .....                   | .....                  | .....                                          | .....                   | .....                  |                                  |
| 30 watts, 55 volts.....        | 24                                                                                                                          | 8.3                    | .....                                            | .....                  | 21                                                             | 127.7                                                              | 10                      | 30                             | 50                                             | 10                      | 80                     | 100                                            | .....                   | .....                  |                                  |
| 16 candlepower, 55 volts.....  | 16                                                                                                                          | 18.7                   | .....                                            | .....                  | .....                                                          | .....                                                              | 3                       | 0                              | 0                                              | 2                       | 100                    | 100                                            | 4                       | 100                    |                                  |
| 50 watts, 55 volts.....        | 4                                                                                                                           | 25                     | .....                                            | .....                  | .....                                                          | .....                                                              | .....                   | .....                          | .....                                          | .....                   | .....                  | .....                                          | .....                   | .....                  |                                  |
| 60 watts, 50 volts.....        | 10                                                                                                                          | 80                     | .....                                            | .....                  | .....                                                          | .....                                                              | .....                   | .....                          | .....                                          | .....                   | .....                  | .....                                          | .....                   | .....                  |                                  |
| 60 watts, 55 volts.....        | 20                                                                                                                          | 95                     | .....                                            | .....                  | .....                                                          | .....                                                              | .....                   | .....                          | .....                                          | .....                   | .....                  | .....                                          | .....                   | .....                  |                                  |
| 32 candlepower, 55 volts.....  | 5                                                                                                                           | 100                    | .....                                            | .....                  | .....                                                          | .....                                                              | 15                      | 60                             | 60                                             | .....                   | .....                  | .....                                          | .....                   | .....                  |                                  |
| 100 watts, 55 volts.....       | 2                                                                                                                           | 100                    | .....                                            | .....                  | .....                                                          | .....                                                              | 8                       | 75                             | 75                                             | 5                       | 60                     | 60                                             | 4                       | 100                    |                                  |
| 120 watts, 55 volts.....       | 10                                                                                                                          | 100                    | .....                                            | .....                  | .....                                                          | .....                                                              | .....                   | .....                          | .....                                          | .....                   | .....                  | .....                                          | .....                   | .....                  |                                  |
| 50 candlepower, 55 volts.....  | 7                                                                                                                           | 100                    | .....                                            | .....                  | .....                                                          | .....                                                              | 5                       | 60                             | 60                                             | .....                   | .....                  | .....                                          | .....                   | .....                  |                                  |
| 155-175 watts, 55 volts.....   | 8                                                                                                                           | 100                    | .....                                            | .....                  | .....                                                          | .....                                                              | .....                   | .....                          | .....                                          | .....                   | .....                  | .....                                          | .....                   | .....                  |                                  |
| 8 candlepower, 110 volts.....  | 8                                                                                                                           | 12.5                   | .....                                            | .....                  | 9                                                              | 228                                                                | 10                      | 80                             | 80                                             | .....                   | .....                  | .....                                          | .....                   | .....                  |                                  |
| 25 watts, 110 volts.....       | 2                                                                                                                           | 0                      | .....                                            | .....                  | 2                                                              | 255                                                                | 7                       | 0                              | 0                                              | 3                       | 100                    | 100                                            | 3                       | 100                    |                                  |
| 30 watts, 110 volts.....       | 12                                                                                                                          | 0                      | .....                                            | .....                  | 2                                                              | 214.3                                                              | .....                   | .....                          | .....                                          | .....                   | .....                  | .....                                          | .....                   | .....                  |                                  |
| 16 candlepower, 110 volts..... | 8                                                                                                                           | 0                      | .....                                            | .....                  | 16                                                             | 214.3                                                              | 15                      | 13.3                           | 50                                             | 15                      | 46.7                   | 100                                            | .....                   | .....                  |                                  |
| 50 watts, 110 volts.....       | 12                                                                                                                          | 8.3                    | .....                                            | .....                  | 10                                                             | 126.0                                                              | 8                       | 12.5                           | 16.7                                           | 3                       | 100                    | 100                                            | 4                       | 100                    |                                  |
| 60 watts, 110 volts.....       | 32                                                                                                                          | 9.4                    | .....                                            | .....                  | 2                                                              | 106.3                                                              | .....                   | .....                          | .....                                          | .....                   | .....                  | .....                                          | .....                   | .....                  |                                  |
| 32 candlepower, 110 volts..... | 6                                                                                                                           | 50                     | .....                                            | .....                  | 15                                                             | 109.1                                                              | 15                      | 13.3                           | 28.6                                           | 10                      | 60                     | 100                                            | .....                   | .....                  |                                  |
| 32 candlepower, 127 volts..... | 8                                                                                                                           | 62.5                   | .....                                            | .....                  | 0                                                              | .....                                                              | 2                       | 0                              | 0                                              | 2                       | 100                    | 100                                            | 3                       | 100                    |                                  |
| 100 watts, 110 volts.....      | 4                                                                                                                           | 75                     | .....                                            | .....                  | .....                                                          | .....                                                              | .....                   | .....                          | .....                                          | .....                   | .....                  | .....                                          | .....                   | .....                  |                                  |
| 120 watts, 110 volts.....      | 48                                                                                                                          | 50                     | .....                                            | .....                  | .....                                                          | .....                                                              | 5                       | 60                             | 75                                             | .....                   | .....                  | .....                                          | .....                   | .....                  |                                  |
| 50 candlepower, 110 volts..... | 7                                                                                                                           | 85.7                   | .....                                            | .....                  | .....                                                          | .....                                                              | 15                      | 33.3                           | 38.5                                           | .....                   | .....                  | .....                                          | .....                   | .....                  |                                  |
| 155 watts, 110 volts.....      | 4                                                                                                                           | 100                    | .....                                            | .....                  | .....                                                          | .....                                                              | 5                       | 100                            | 100                                            | .....                   | .....                  | .....                                          | .....                   | .....                  |                                  |
| 175 watts, 110 volts.....      | 4                                                                                                                           | 100                    | .....                                            | .....                  | .....                                                          | .....                                                              | 5                       | 20                             | 40                                             | .....                   | .....                  | .....                                          | .....                   | .....                  |                                  |
| 8 candlepower, 220 volts.....  | 3                                                                                                                           | 0                      | .....                                            | .....                  | .....                                                          | .....                                                              | 5                       | 20                             | 25                                             | .....                   | .....                  | .....                                          | .....                   | .....                  |                                  |
| 35 watts, 220 volts.....       | 14                                                                                                                          | 0                      | .....                                            | .....                  | 2                                                              | 350.0                                                              | 5                       | 20                             | 100                                            | 2                       | 100                    | 100                                            | 3                       | 100                    |                                  |
| 16 candlepower, 220 volts..... | 5                                                                                                                           | 0                      | .....                                            | .....                  | 9                                                              | 348.8                                                              | 20                      | 5                              | 33.3                                           | 18                      | 44.4                   | 80                                             | .....                   | .....                  |                                  |
| .....                          | .....                                                                                                                       | .....                  | .....                                            | .....                  | 5                                                              | 206                                                                | 11                      | 0                              | 0                                              | 5                       | 40                     | 100                                            | 4                       | 100                    |                                  |



|                                    |    |      |       |       |       |       |    |      |      |       |       |       |       |       |       |       |
|------------------------------------|----|------|-------|-------|-------|-------|----|------|------|-------|-------|-------|-------|-------|-------|-------|
| 60 watts, 220 volts.....           | 22 | 4.5  | ..... | ..... | 24    | 181.8 | 15 | 13.3 | 33.3 | 15    | 66.7  | 100   | ..... | 4     | ..... | 100   |
| 32 candlepower, 220 volts.....     | 7  | 0    | ..... | ..... | 9     | 120.2 | 3  | 33.3 | 50   | 3     | 66.7  | 66.7  | ..... | ..... | ..... | ..... |
| 120 watts, 220 volts.....          | 44 | 2.3  | ..... | ..... | 21    | 116.8 | 20 | 20   | 22.2 | 10    | 80    | 80    | ..... | ..... | ..... | ..... |
| 50 candlepower, 220-225 volts..... | 20 | 80   | ..... | ..... | ..... | ..... | 6  | 66.7 | 80.0 | 2     | 100   | 100   | ..... | 2     | ..... | 100   |
| 190 watts, 220 volts.....          | 16 | 68.7 | ..... | ..... | ..... | ..... | 10 | 50   | 62.5 | ..... | ..... | ..... | ..... | ..... | ..... | ..... |
| 25 watts, 110 volts.....           | 7  | 85.7 | ..... | ..... | ..... | ..... | 4  | 75   | 75   | ..... | ..... | ..... | ..... | ..... | ..... | ..... |
| 2 5 watts, 220 volts.....          | 14 | 28.6 | ..... | ..... | ..... | ..... | 6  | 0    | 0    | ..... | ..... | ..... | ..... | ..... | ..... | ..... |

*a* The manufacturers' ratings are given. The approximate candlepower of any standard lamp rated in watts may be ascertained by dividing the wattage rating by 3.5 in the case of carbon-filament lamps and by 1.25 in the case of tungsten-filament lamps. All lamps tested were carbon-filament lamps except those represented by the last two items, which were tungsten-filament lamps.

*b* Additional results are given in Table 6.

*c* Normal wattage as here given is the wattage of the lamp at rated voltage as distinguished from the rated wattage of the lamp.

## DISCUSSION.

The results of the tests of the standard lamps were satisfactory in that positive results were obtained in almost every case. The purpose of the tests was to determine whether certain specific sizes of incandescent lamps would when broken ignite explosive mixtures of gas and air. The results obtained showed that gaseous mixtures could be ignited by all the classes of standard lamps tested and also by all the classes of miniature lamps that gave sufficient light to be of commercial value. Although some classes of lamps gave comparatively few ignitions, the unsafe character of such lamps was indicated by even a single ignition under conditions that might exist in actual practice.

## SMASH TESTS (SERIES 1).

Series 1 tests included tests of both standard and miniature lamps. In table 4 the results of series 1-A and 1-B are combined with those of series 1, as the behavior of the lamps was the same in all three series.

In the tests of series 1-A, made with alternating current, 25 ignitions were obtained from 80 trials, as compared to 26 ignitions from 80 trials in the tests of series 1 made with direct current. In the tests of series 1-B, made with series-connected lamps, 11 ignitions were obtained from 50 trials, as compared to 14 ignitions from 50 trials made with similar lamps connected in multiple (series 1).

The results presented in table 4 demonstrate that the standard lamps that ignite gas least readily are those of low candlepower and high voltage. The only lamps that, in some brand, did not ignite gas were those of the 8-candlepower, 220-volt class. Lamps of the 16-candlepower, 220-volt and 32-candlepower, 220-volt classes failed to ignite gas in some brands, but gave ignition in others.

There is a seeming lack of uniformity in the number of lamps of each rating tested. This is due to the fact that the lamps were tested by general classes rather than by brands or ratings. As an additional reason, the tests of series 1-C and 1-D showed so conclusively the characteristics of certain sizes of lamps that it was not thought necessary to multiply repetitions of the series 1 tests. Not less than 80 smash tests of one form or another were made of each general class of lamp concerning whose ability to ignite gas there was any doubt.

Standard incandescent lamps for underground use are usually 16-candlepower, 110 to 250 volt lamps. Sixty-two carbon lamps and 7 tungsten lamps of the 16-candlepower, 110-volt class were tested by direct smashing while burning at rated voltage. Five of the carbon and 6 of the tungsten lamps ignited the gas. Twenty-seven



carbon lamps and 14 tungsten lamps of the 16-candlepower, 220-volt class were tested by direct smashing while burning at rated voltage. One of the carbon lamps and 4 of the tungsten lamps ignited the gas. The carbon lamp produced ignition by the short-circuiting of its filament.

The percentage of ignitions given by the several classes of lamps is graphically shown in figure 1. The figure indicates that 55-volt and 110-volt lamps of all candlepowers ignited gas under the conditions of the series 1 tests, that 32 and 50 candlepower, 55-volt lamps invariably ignited the gas, that the 8-candlepower, 220-volt lamps gave no ignitions, and that in general the percentage of ignitions obtained from lamps of a given candlepower decreased as the voltage increased.

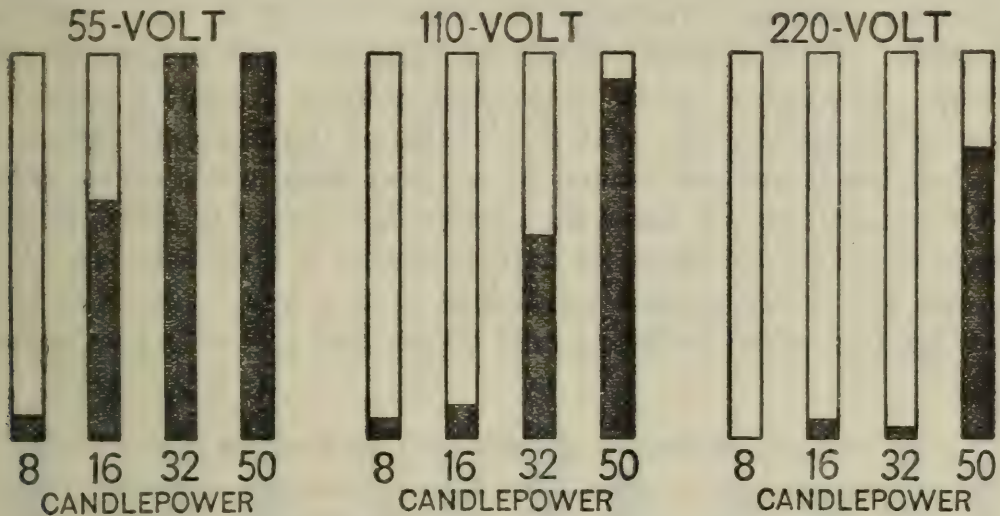


FIGURE 1.—Diagram representing comparative percentages of ignitions in smash tests. Shaded parts represent ignitions; unshaded parts represent failures to ignite.

#### SMASH TESTS (SERIES 1-A AND 1-B).

Series 1-A and 1-B tests were made with standard lamps only. As stated above the behavior of the lamps was the same as in the tests of series 1.

#### SMASH TESTS (SERIES 1-C).

The tests of series 1-C were made with both standard and miniature lamps. The results showed that any standard or miniature lamp that would cause ignition of gas in the most explosive mixture would, under similar conditions, ignite mixtures containing from 5 to 11.5 per cent of gas.

None of the lamps ignited mixtures containing more than 12 or less than 5 per cent of gas.

SMASH TESTS (SERIES 1-D).

Series 1-D tests were made with both standard and miniature lamps.

The tests of standard lamps were made for two purposes, first to confirm by positive results the negative results of the series 1 tests, and second to btain a means of comparing the relative safety of such lamps as did not cause ignition in the series 1 tests.

The tests achieved the purpose for which they were undertaken. Lamps that gave negative results in the tests of series 1 gave no ignitions in the series 1-D tests until their energy consumption had been increased by at least 26 per cent (see table 4, 16-candlepower, 110-volt lamp).

Table 4 gives, for each brand of standard lamps tested, the number of ignitions and the percentage of normal wattage at which ignition took place. Table 5 gives similar information for each general class of lamp. The figures given in the fifth column of table 5 provide a means of comparing the relative abilities of the lamps to ignite the gas when the lamps are broken by a direct blow while under rated-voltage conditions. A lamp that causes ignition only when its filament is radiating 3.5 times its normal energy is obviously less likely to ignite gas under normal conditions than a lamp that invariably causes ignition when radiating only 30 per cent more than its normal energy.

TABLE 5.—Summary of results of tests in series 1-D.

| Approximate rating of lamps. |        |        | Number of ignitions. | Percentage of normal wattage causing ignitions. |                               |                       |
|------------------------------|--------|--------|----------------------|-------------------------------------------------|-------------------------------|-----------------------|
| Candle-power.                | Watts. | Volts. |                      | Minimum. <sup>a</sup>                           | Average minimum. <sup>b</sup> | Average. <sup>c</sup> |
| 8                            | 30     | 55     | 27                   | 128                                             | 135                           | 142                   |
| 8                            | 25-30  | 110    | 24                   | 214                                             | 232                           | 239                   |
| 16                           | 50-60  | 110    | 27                   | <sup>d</sup> 106                                | 119                           | 126                   |
| 8                            | 35     | 220    | 11                   | 349                                             | 364                           | 365                   |
| 16                           | 60     | 220    | 27                   | 182                                             | 199                           | 205                   |
| 32                           | 120    | 220    | 30                   | 117                                             | 126                           | 132                   |

<sup>a</sup> Minimum percentage of normal wattage (See footnote, table 4) at which an ignition was obtained from any brand of lamp.

<sup>b</sup> Average minimum percentage of normal wattage for all brands.

<sup>c</sup> Average percentage of normal wattage for all tests giving an ignition.

<sup>d</sup> This brand of lamp gave ignitions at normal wattage in 8.3 per cent of the series 1 tests (see table 4, 50-watt, 110-volt lamp).

TIP-BREAKING TESTS (SERIES 2).

The tests of series 2 were made with standard lamps only. The results of the tests showed that practically every class of standard lamps will ignite gas if the tips are removed in a certain way. The size of the hole left by the removal of the tip has an important



bearing upon whether or not ignition will occur. Small filaments are most likely to ignite when the hole is small; the reverse is true with large filaments. There are three conditions that may exist after the tip has been removed:

The filament may be distorted and broken by the entering gas (Pl. VI, *A*); the filament may remain intact but be cooled by the entering gas below the ignition point of the gas, recovering its temperature later and burning off after igniting the gas (Pl. VI, *B*); the filament may ignite the gas as it enters, thus producing a partial explosion that temporarily checks the entrance of gas and fills the bulb with the products of combustion.

These conditions are stated in the order of the violence of the gas entrance. The first and last are at either extreme and produce no ignition. The second condition which depends upon the proper relation of filament diameter to gas-entrance velocity is the only

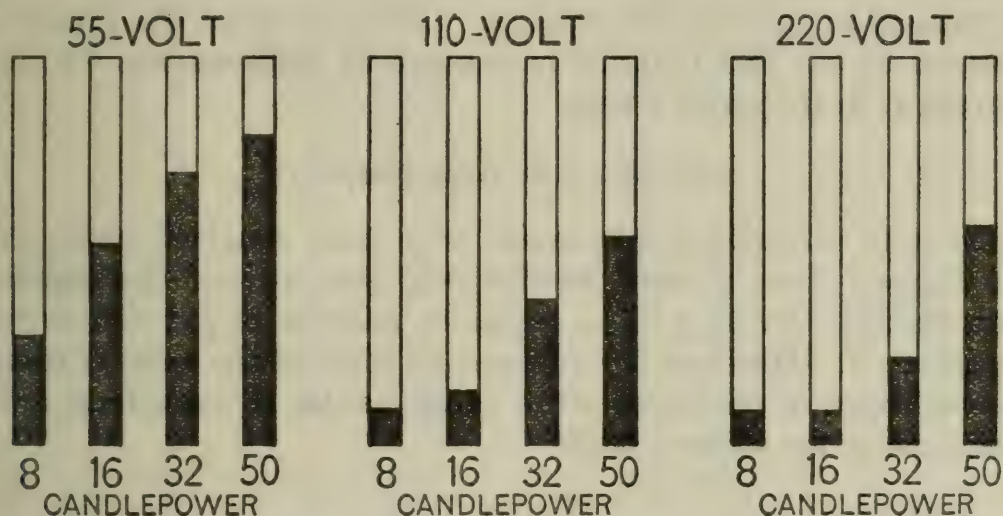


FIGURE 2.—Diagram representing comparative percentages of ignitions in tip-breaking tests. Shaded parts represent ignitions; unshaded parts represent failures to ignite.

one that causes ignitions, but does so invariably. Wherever in table 4 less than 100 per cent of ignitions from unbroken filaments is reported, the third condition prevailed in some of the tests. Wherever the percentage of ignitions does not agree with the percentage of ignitions from unbroken filaments, the first condition prevailed in some of the tests.

Figure 2 shows graphically the percentage of ignitions obtained from the various classes of lamps. The figure shows that the percentage of ignitions increased as the candlepower rating increased and decreased as the voltage rating increased, and that although no class of lamps gave 100 per cent of ignitions, all classes produced some ignitions. Although the average percentage of ignitions in the tests of series 2 is less than that in the tests of series 1, the former tests

proved to be the more severe because they showed that every class of lamp could cause ignition. The tip-breaking and the smash tests are both practical. In the majority of underground lighting systems, the tip of the bulb is the most exposed part of the lamp and lamps are often destroyed by having their tips broken off.

#### PUNCTURE TESTS (SERIES 3).

The tests of series 3, made with standard lamps only, were similar in character to those of series 2, the principal differences being that the gas entered through larger holes and did not impinge directly upon the filaments. Under these conditions the filaments were greatly cooled, but were not broken. As compared to the tests of series 2, the percentage of unbroken filaments was 1.45 times as great. The cooling of the filaments is evidenced by the high percentage of ignitions from unbroken filaments, which was 2.5 times as great as in the tests of series 2. The severity of the conditions is shown by the fact that the percentage of ignitions was 3.6 times as great as in the series 2 tests.

#### NAKED-FILAMENT TESTS (SERIES 4).

The tests of series 4 were made with both standard and miniature lamps. They showed conclusively that any of the standard lamp filaments burning in an explosive mixture of gas will eventually ignite it. This fact is confirmed by some of the series 3 results, the conditions in the latter series being similar in some tests to the conditions in the series 4 tests.



## RESULTS OF MINIATURE-LAMP TESTS.

## TABULATION.

A tabulation of the general results of the tests of miniature lamps follows:

TABLE 6.—*Number of tests made with miniature lamps,<sup>a</sup> and percentage of ignitions obtained.*

| Manufacturer's rating. |        |          | Number of lamps tested. | Series No. | Conditions of test.                       |                       |                 | Results of test.     |                          |                                                         |
|------------------------|--------|----------|-------------------------|------------|-------------------------------------------|-----------------------|-----------------|----------------------|--------------------------|---------------------------------------------------------|
| Candle-power.          | Volts. | Amperes. |                         |            | Percentage of rated voltage. <sup>b</sup> | Gas percentage.       | Bulb broken by— | Number of ignitions. | Percentage of ignitions. | Minimum percentage of rated voltage giving an ignition. |
| 0.5                    | 1.5    | 0.40     | 10                      | 1-D        | 132.7                                     | 8.6                   | Smashing...     | 1                    | 10.0                     | 132.7                                                   |
| .5                     | 1.5    | .40      | 2                       | 4          | 138.7                                     | 8.6                   | (c)             | 1                    | 50.0                     | 138.7                                                   |
| .....                  | 2.0    | .23      | 9                       | 1-D        | 120.0                                     | 8.6                   | Smashing...     | 3                    | 33.3                     | 110.0                                                   |
| .....                  | 2.0    | .23      | 3                       | 1-D        | 148.5                                     | 8.6                   | (c)             | 1                    | 33.3                     | 148.5                                                   |
| .....                  | 2.0    | .40      | 4                       | 1          | 100.0                                     | 8.6                   | Smashing...     | 1                    | 25.0                     | 100.0                                                   |
| .....                  | 2.0    | .40      | 5                       | 1-D        | 108.8                                     | 8.6                   | do.....         | 2                    | 40.0                     | 107.5                                                   |
| 1.0                    | 2.0    | .....    | 9                       | 1          | 100.0                                     | 8.6                   | do.....         | 7                    | 77.8                     | 95.0                                                    |
| .....                  | 2.0    | .43      | 8                       | 1          | 96.7                                      | 8.6                   | do.....         | 3                    | 37.5                     | 95.5                                                    |
| .....                  | 2.0    | .43      | 4                       | 1-D        | 108.0                                     | 8.6                   | do.....         | 4                    | 100.0                    | 106.0                                                   |
| .....                  | 2.0    | .53      | 1                       | 1          | 98.5                                      | 8.6                   | do.....         | 1                    | 100.0                    | 98.5                                                    |
| .....                  | 2.0    | .53      | 4                       | 1-D        | 102.8                                     | 8.6                   | do.....         | 3                    | 75.0                     | 101.0                                                   |
| .....                  | 2.0    | .73      | 5                       | 1          | 94.5                                      | 8.6                   | do.....         | 3                    | 60.0                     | 90.0                                                    |
| 1.0                    | 2.5    | .30      | 11                      | 1          | 100.0                                     | 8.6                   | do.....         | 7                    | 63.6                     | 100.0                                                   |
| 1.0                    | 2.5    | .30      | 12                      | 1-C        | 100.0                                     | 5 to 6 and 11 to 11.5 | do.....         | 4                    | 33.3                     | 100.0                                                   |
| 1.0                    | 2.5    | .....    | 10                      | 1          | 100.0                                     | 8.6                   | do.....         | 3                    | 30.0                     | 100.0                                                   |
| 1.5                    | 3.5    | .30      | 23                      | 1          | 99.2                                      | 8.6                   | do.....         | 16                   | 69.6                     | 98.6                                                    |
| 1.5                    | 3.5    | .30      | 21                      | 1-C        | 100.0                                     | 5 to 6 and 11 to 12.5 | do.....         | 12                   | 57.1                     | 100.0                                                   |
| 2.0                    | 4.0    | .....    | 10                      | 1          | 82.2                                      | 8.6                   | do.....         | 7                    | 70.0                     | 70.0                                                    |
| .....                  | 4.0    | .53      | 5                       | 1          | 94.9                                      | 8.6                   | do.....         | 5                    | 100.0                    | 91.3                                                    |
| 2.0                    | 4.5    | .....    | 10                      | 1          | 85.3                                      | 8.6                   | do.....         | 7                    | 70.0                     | 71.1                                                    |
| 2.0                    | 5.5    | .30      | 9                       | 1          | 98.8                                      | 8.6                   | do.....         | 6                    | 66.7                     | 78.0                                                    |
| 2.0                    | 5.5    | .30      | 12                      | 1-C        | 100.0                                     | 5 to 7 and 11.5 to 12 | do.....         | 11                   | 91.7                     | 100.0                                                   |
| .....                  | 6.0    | .30      | 5                       | 1          | 88.2                                      | 8.6                   | do.....         | 5                    | 100.0                    | 88.0                                                    |
| (d)                    | 2.5    | (d)      | 2                       | 1-D        | e 103.0                                   | 8.6                   | do.....         | 0                    | .....                    | .....                                                   |
| (d)                    | 2.5    | (d)      | 5                       | 4          | 168.0                                     | 8.6                   | (c)             | 1                    | 20.0                     | 168.0                                                   |
| (f)                    | 3.5    | (f)      | 10                      | 1          | e 99.2                                    | 8.6                   | Smashing...     | 0                    | .....                    | .....                                                   |
| (f)                    | 3.5    | (f)      | 7                       | 1-D        | 137.1                                     | 8.6                   | do.....         | 2                    | 28.6                     | 137.1                                                   |
| (f)                    | 3.5    | (f)      | 5                       | 4          | 142.9                                     | 8.6                   | (c)             | 2                    | 40.0                     | 142.9                                                   |
| (g)                    | 5.5    | (g)      | 4                       | 1          | e 98.2                                    | 8.6                   | Smashing...     | 0                    | .....                    | .....                                                   |
| (g)                    | 5.5    | (g)      | 6                       | 1-D        | 105.2                                     | 8.6                   | do.....         | 4                    | 66.7                     | 103.8                                                   |
| (g)                    | 5.5    | (g)      | 3                       | 4          | 101.5                                     | 8.6                   | (c)             | 1                    | 33.3                     | 101.5                                                   |

<sup>a</sup> The lamps had tungsten filaments, except those represented by the last eight items, which were carbon-filament lamps.

<sup>b</sup> The values given in this column are the average values of the voltage impressed upon such lamps as caused ignition.

<sup>c</sup> Naked-filament tests.

<sup>d</sup> These lamps had no current or candlepower rating, but consumed in test about 0.20 ampere.

<sup>e</sup> Average voltage impressed upon the lamps tested, whether causing ignition or not.

<sup>f</sup> These lamps had no current or candlepower rating, but consumed in test about 0.35 ampere.

<sup>g</sup> These lamps had no current or candlepower rating, but consumed in test about 0.30 ampere.

## DISCUSSION.

Miniature lamps can not be divided into as distinct classes as are standard lamps, because the demands of the service to which miniature lamps are put are quite different. On account of the desirability of using as light a battery as possible, miniature lamps are often

operated at higher temperatures than standard lamps, with a proportionately increased efficiency and decreased length of life. A single lamp may be variously rated according to the needs of the purchaser as to the candlepower, voltage, current consumption, or life.

Another variable that affects the performance of miniature lamps is the voltage of the battery with which the lamps are used. There are no standard voltages for this class of service. For portable lights there is available almost any voltage from 1.3 to 7. These voltages are not constant during the length of life of the battery or charge, and at the beginning lamps must be used at overvoltage in order to give a satisfactory average performance. These facts should be borne in mind while examining table 6, which summarizes the results obtained from the tests of miniature lamps.

The results presented in table 6 show that none of the carbon-filament lamps ignited gas under the conditions of the series 1 (smash) tests. In fact, no ignitions from carbon-filament lamps burning at rated voltage were obtained in the tests of any of the series. An ignition with a potential 4 per cent above rated voltage was obtained from a carbon lamp of the 5.5-volt class under the conditions of the series 1-D tests. Carbon lamps of all the other classes gave little light and would be of little practical use in mines.

Fifteen classes of tungsten lamps were tested under series 1 conditions. All ignited gas except the lamps of the 2-volt, 0.23-ampere class, and the lamps of the 1.5-volt, 0.4-ampere class. The former gave an ignition in a later test with a 20 per cent overvoltage, and the latter with a 33 per cent overvoltage. Both of these lamps gave about 0.5 candlepower.

These tests showed that it is quite probable that any miniature lamp that gives enough light to be of practical use in a mine will ignite explosive mixtures of gas and air if the bulb is so broken that the filament is not injured.

Table 6 shows the results obtained from the smash tests, under series 1-D conditions, of nine classes of miniature lamps. The number of ignitions has been related to the impressed voltage in percentage of rated voltage instead of to the energy consumption in percentage of normal wattage, as with the standard lamps. This was done because the series 1-D tests were of an arbitrary nature so far as standard lamps were concerned, and were made principally to determine the "factor of safety" of the various lamps. For this purpose the wattage absorbed by the filament is the best indication, as it governs the temperature of the filament and hence the quantity of stored heat.

In the case of the miniature lamps, however, the tests were practical, as these lamps are often purposely used at greater than rated voltage, and may be used, through accident or ignorance, at voltages



much higher than those at which the lamps are rated. The relative danger under such conditions was better shown by the increase in voltage than by the increase in wattage. The maximum overvoltage required to give ignition in these tests was approximately 37 per cent for carbon lamps and 33 per cent for tungsten lamps.

Only a few miniature lamps were tested under series 4 (naked filament) conditions. The lamps tested were of a class that had not caused ignition when smashed at rated voltage. Only one of these lamps gave an ignition at rated voltage under the series 4 conditions.

The tests showed that the naked filaments of miniature lamps will not invariably cause ignition, as the naked standard filaments do, when burned to extinction in explosive mixtures.

### IMMEDIATE CAUSE OF IGNITION.

It was not regarded as absolutely essential to the value of the investigation here reported that the specific cause of ignition of the gas be determined. Other investigators, however, have been much interested in this phase; consequently, certain observations are reported herein that bear upon the question of whether the ignition is caused by the glowing filament alone or by the spark that occurs when the filament is ruptured.

That glowing filaments may ignite gas seems to be proved by the fact that in 58 tests in which the gas was ignited the filaments continued to glow 2 to 59 seconds after ignition had taken place.

The tests did not prove so conclusively that the spark that occurs when the filaments are broken is not the cause of gas ignition, although the following evidence seems to show that the unassisted spark can not ignite gas: Fifty tests made upon 50, 60, and 120 watt lamps, each of 110 volts, showed a greater percentage of ignitions when the lamps were connected in multiple than when they were connected in series, although the breaking spark was drawn at 110 volts with the lamps in multiple as against 550 volts with the lamps in series.

By breaking a noninductive 550-volt circuit between a steel contact and a carbon contact, it was found that when the current exceeded 0.15 ampere an ignition was always obtained when the circuit was opened. Yet 10 tests made with five 110-volt lamps connected in series across 550 volts produced no ignition, although the filament of the tested lamp carried one-half an ampere, and the spark must have been drawn at 550 volts. Neither were ignitions obtained from 11 similar tests made with lamps carrying approximately 1 ampere.

The authors believe that the spark that is drawn when a lamp filament is broken is to a great extent "blown out" by the entering current of gas. To prove this assumption, a 50-watt, 55-volt naked filament was connected in series with noninductive resistance and 0.5

ampere (one-half normal current) at 110 volts was passed through the circuit. The filament was then broken by gradual pressure, which distorted it until it snapped off. Five ignitions were obtained from six tests made in this way. Similar lamps were then connected in series with noninductive resistance across 550 volts, and the filaments were disrupted by smashing the lamp bulbs. Five tests were made, three with a current of 0.6 ampere and two with a current of 0.7 ampere. No ignition was obtained in any of the five trials, although the current was 20 to 40 per cent greater and the voltage 400 per cent greater than in the five tests that gave ignitions with the naked filaments. It is therefore manifest that the intruding gas has a quenching effect upon the spark.

Five tests were then made by connecting a 175-watt, 55-volt lamp (normal current 3.5 amperes) in series with a noninductive resistance of such value that 2.25 amperes flowed through the filament when 550 volts was impressed across the lamp and resistance. The lamp was surrounded with gas and smashed while carrying this current. No ignition resulted from five trials, although the current broken was greater and the voltage ten times as great as in the case of lamps<sup>a</sup> that invariably produced ignitions when broken while burning under normal conditions.

It is manifest that the spark alone did not cause these ignitions, if ignition could not be caused by a similar spark with ten times the voltage behind it.

#### AUTHORS' THEORY OF THE IGNITION PHENOMENON.

The authors are inclined to believe that the likelihood of gas<sup>b</sup> ignition by standard carbon-filament lamps is a function of the cross section of the filaments. The filaments of 24 different types of standard lamps were measured<sup>c</sup> and the cross sections of the filaments were compared to their tendency to ignite gas, as expressed in percentage of ignitions obtained in a given number of trials. All filaments having a cross section of 0.000177 square centimeter or less failed to ignite gas in the series 1 tests. All filaments having a cross section of 0.000234 square centimeter or more invariably ignited gas under the conditions of the series 1 tests; filaments having a cross section of 0.000194 square centimeter ignited gas in 50 per cent of the trials; and filaments having a cross section of 0.000215 square centimeter ignited gas in 83 per cent of the trials. It is true that a similar

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<sup>a</sup> See table 4, 32-candlepower, 55-volt lamps; 100-watt, 55-volt lamps; and 120-watt, 55-volt lamps.

<sup>b</sup> See definition on p. 7.

<sup>c</sup> These measurements were made with a microscope by Reinhardt Thiessen, assistant chemist of the Bureau of Mines. Three sets of readings were taken, one with a micrometer eyepiece and two with a camera lucida.



relation existed between the current flowing in the filaments and the percentage of ignitions that they gave, but the authors do not regard this relation as significant, because they believe that the spark that is drawn when a filament is broken is not responsible for the ignition of gas.

If the bulb of a glowing incandescent lamp is smashed while surrounded by an explosive mixture, and if the filament is not broken by the jar of the blow, the filament is first cooled by the intrushing mixture and then broken by it. Of course the cooling and the breaking are almost simultaneous, but the authors believe that ignition, if it occurs, takes place during the period of cooling and before the filament is broken.

If this hypothesis is correct, there are two reasons why large filaments ignite gas more readily than smaller ones: First, the temperature of the larger filaments will not be so greatly reduced before they are broken; and, second, the larger filaments will not so quickly succumb to the breaking action of the intrushing gas.

The authors are not yet certain whether the ignition of gas by standard tungsten lamps is caused by the normal heat of the filaments or by abnormal temperatures resulting from a short circuit of the filament.

It is probable that miniature lamps ignite gas by virtue of their glowing filaments, as the sparks produced when the filaments are broken are small, and in many tests the filaments were observed to glow after ignition had taken place.

#### SUMMARY OF DEDUCTIONS.

The investigation showed that the naked filaments of all standard lamps, energized at rated voltage, will ignite gas (the explosive gaseous mixture used); that all classes of standard carbon lamps will sometimes ignite gas when the tips of the bulbs are broken off in the presence of those mixtures; that the filament temperature of all classes of standard lamps and of all but one class of miniature lamps can be increased to such a degree that the lamps when smashed will ignite gas; that several classes of both standard and miniature lamps when smashed while burning at rated voltage will invariably ignite gas; that certain other classes of both standard and miniature lamps under the circumstances last mentioned will not usually ignite gas.

Based upon the results of the investigation, the table following gives deductions as to the probability of igniting gas by each class of lamp examined.

TABLE 7.—Probability of gas ignition at rated voltage by each class of lamps tested.<sup>a</sup>

| Classification of lamp. |                        |                           |                      | Condition of lamp.          | Ignition of gas.       |
|-------------------------|------------------------|---------------------------|----------------------|-----------------------------|------------------------|
| Size.                   | Character of filament. | Approximate candle-power. | Approximate voltage. |                             |                        |
| Standard...             | Carbon....             | 50                        | 55                   | Bulb completely smashed...  | Certain.               |
| Do.....                 | do.....                | 32                        | 55                   | do.....                     | Do.                    |
| Do.....                 | do.....                | 50                        | 110                  | do.....                     | Almost certain.        |
| Do.....                 | do.....                | 50                        | 220                  | do.....                     | Do.                    |
| Do.....                 | do.....                | 16                        | 55                   | do.....                     | Do.                    |
| Do.....                 | do.....                | 32                        | 110                  | do.....                     | Frequent.              |
| Do.....                 | do.....                | 8                         | 55                   | do.....                     | Occasional.            |
| Do.....                 | do.....                | 16                        | 110                  | do.....                     | Do.                    |
| Do.....                 | do.....                | 32                        | 220                  | do.....                     | Rare.                  |
| Do.....                 | do.....                | 16                        | 220                  | do.....                     | Do.                    |
| Do.....                 | do.....                | 8                         | 110                  | do.....                     | Do.                    |
| Do.....                 | do.....                | 8                         | 220                  | do.....                     | Unlikely. <sup>b</sup> |
| Do.....                 | do.....                | 50                        | 55                   | Tip of bulb broken off..... | Almost certain.        |
| Do.....                 | do.....                | 32                        | 55                   | do.....                     | Do.                    |
| Do.....                 | do.....                | 50                        | 110                  | do.....                     | Frequent.              |
| Do.....                 | do.....                | 50                        | 220                  | do.....                     | Do.                    |
| Do.....                 | do.....                | 16                        | 55                   | do.....                     | Do.                    |
| Do.....                 | do.....                | 32                        | 110                  | do.....                     | Do.                    |
| Do.....                 | do.....                | 8                         | 55                   | do.....                     | Do.                    |
| Do.....                 | do.....                | 32                        | 220                  | do.....                     | Occasional.            |
| Do.....                 | do.....                | 16                        | 110                  | do.....                     | Do.                    |
| Do.....                 | do.....                | 8                         | 110                  | do.....                     | Do.                    |
| Do.....                 | do.....                | 16                        | 220                  | do.....                     | Do.                    |
| Do.....                 | do.....                | 8                         | 220                  | do.....                     | Do.                    |
| Do.....                 | Tungsten               | 20                        | 110                  | Bulb completely smashed...  | Almost certain.        |
| Do.....                 | do.....                | 20                        | 220                  | do.....                     | Frequent.              |
| Do.....                 | do.....                | 20                        | 110                  | Tip of bulb broken off..... | Almost certain.        |
| Do.....                 | do.....                | 20                        | 220                  | do.....                     | Unlikely. <sup>b</sup> |
| Miniature...            | do.....                | 2.0                       | 4-6                  | Bulb completely smashed...  | Certain.               |
| Do.....                 | do.....                | 1.5                       | 2-3.5                | do.....                     | Almost certain.        |
| Do.....                 | do.....                | 1.0                       | 2-2.5                | do.....                     | Frequent.              |
| Do.....                 | do.....                | .5                        | 1.5-2                | do.....                     | Unlikely.              |

<sup>a</sup> The results of tests of the miniature carbon-filament lamps are not included in this table because those lamps were rated in voltage only and hence their behavior could not be used as a standard of comparison.  
<sup>b</sup> No ignitions were obtained in any of the tests of this lamp made under the condition stated.

PUBLICATIONS ON MINE ACCIDENTS AND TESTS OF EXPLOSIVES.

The following Bureau of Mines publications may be obtained free by applying to the Director, Bureau of Mines, Washington, D. C.:

BULLETIN 10. The use of permissible explosives, by J. J. Rutledge and Clarence Hall. 1912. 34 pp., 5 pls.

BULLETIN 15. Investigations of explosives used in coal mines, by Clarence Hall, W. O. Snelling, and S. P. Howell, with a chapter on the natural gas used at Pittsburgh, by G. A. Burrell, and an introduction by O. E. Munroe. 1911. 197 pp., 7 pls.

BULLETIN 17. A primer on explosives for coal miners, by C. E. Munroe and Clarence Hall. 61 pp., 10 pls. Reprint of United States Geological Survey Bulletin 423.

BULLETIN 20. The explosibility of coal dust, by G. S. Rice, with chapters by J. C. W. Frazer, Axel Larsen, Frank Haas, and Carl Scholz. 204 pp., 14 pls. Reprint of United States Geological Survey Bulletin 425.

BULLETIN 44. First national mine-safety demonstration, by H. M. Wilson and A. H. Fay, with a chapter on the explosion at the experimental mine, by G. S. Rice. 1912. 75 pp., 4 pls.



BULLETIN 46. An investigation of explosion-proof mine motors, by H. H. Clark. 1912. 44 pp., 6 pls.

BULLETIN 48. The selection of explosives used in engineering and mining operations, by Clarence Hall and S. P. Howell. 1912. 50 pp. 3 pls.

TECHNICAL PAPER 4. The electrical section of the Bureau of Mines, its purpose and equipment, by H. H. Clark. 1911. 12 pp.

TECHNICAL PAPER 6. The rate of burning of fuse as influenced by temperature and pressure, by W. O. Snelling and W. C. Cope. 1912. 28 pp.

TECHNICAL PAPER 7. Investigations of fuse and miners' squibs, by Clarence Hall and S. P. Howell. 1912. 19 pp.

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TECHNICAL PAPER 19. The factor of safety in mine electrical installations, by H. H. Clark. 1912. 14 pp.

TECHNICAL PAPER 21. The prevention of mine explosions; report and recommendations, by Victor Watteyne, Carl Meissner, and Arthur Desborough. 12 pp. Reprint of United States Geological Survey Bulletin 369.

TECHNICAL PAPER 23. Ignition of mine gas by miniature electric lamps, by H. H. Clark. 1912. 5 pp.

TECHNICAL PAPER 24. Mine fires, a preliminary study, by G. S. Rice. 1912. 51 pp.

TECHNICAL PAPER 28. Ignition of mine gas by standard incandescent lamps, by H. H. Clark. 1912. 6 pp.

MINERS' CIRCULAR 3. Coal-dust explosions, by G. S. Rice. 1911. 22 pp.

MINERS' CIRCULAR 4. The use and care of mine rescue breathing apparatus, by J. W. Paul. 1911. 24 pp.

MINERS' CIRCULAR 5. Electrical accidents in mines; their causes and prevention, by H. H. Clark, W. D. Roberts, L. C. Ilsley, and H. F. Randolph. 1911. 10 pp., 3 pls.

MINERS' CIRCULAR 6. Permissible explosives tested prior to January 1, 1912, and precautions to be taken in their use, by Clarence Hall. 1912. 20 pp.

MINERS' CIRCULAR 9. Accidents from falls of roof and coal, by G. S. Rice. 1912. 16 pp.

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